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Advanced AE Techniques in Composite Materials Research

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Abstract

Advanced, waveform based acoustic emission (AE) techniques have been successfully used to evaluate damage mechanisms in laboratory testing of composite coupons. An example is presented in which the initiation of transverse matrix cracking was monitored. In these tests, broad band, high fidelity acoustic sensors were used to detect signals which were then digitized and stored for analysis. Analysis techniques were based on plate mode wave propagation characteristics. This approach, more recently referred to as Modal AE, provides an enhanced capability to discriminate and eliminate noise signals from those generated by damage mechanisms. This technique also allows much more precise source location than conventional, threshold crossing arrival time determination techniques. To apply Modal AE concepts to the interpretation of AE on larger composite specimens or structures, the effects of modal wave propagation over larger distances and through structural complexities must be well characterized and understood. To demonstrate these effects, measurements of the far field, peak amplitude attenuation of the extensional and flexural plate mode components of broad band simulated AE signals in large composite panels are discussed. These measurements demonstrated that the flexural mode attenuation is dominated by dispersion effects. Thus, it is significantly affected by the thickness of the composite plate. Furthermore, the flexural mode attenuation can be significantly larger than that of the extensional mode even though its peak amplitude consists of much lower frequency components.

1. Introduction

The capabilities of AE testing in composite materials research have been significantly improved by several recent advances. These include the development of digital, waveform based, acquisition instrumentation with sufficient memory and acquisition rates for AE testing. Another important development has been the improvements in high fidelity, high sensitivity, broadband sensors. However, most important has been the increased understanding of the nature of AE signal propagation as guided acoustic modes in common testing specimen geometries such as thin plates and coupons (Gorman, 1991; Gorman and Prosser, 1991; Prosser, 1991). Analysis of guided mode AE signals has been designated Modal AE. It has led to significantly improved AE source location accuracy (Ziola and Gorman, 1991). Modal AE has also provided the capability to better differentiate AE signals from different source mechanisms including extraneous noise (Ono, 1994 and Prosser et al., 1995).

Two sets of Modal AE measurements are presented herein. The first is an example of a successful application in composite materials research to monitor the initiation of transverse matrix cracking in cross-ply graphite/epoxy coupons. In these experiments, noise signals created by damage in the grip region were differentiated from crack signals by waveform analysis. The signals from matrix cracks contained a higher amplitude extensional plate mode component with little or no flexural mode. The grip damage signals contained significant flexural mode components.

The second set of data are measurements of the peak amplitude attenuation of the extensional and flexural plate modes in large composite plates. The flexural mode suffered considerably more amplitude loss even though its frequency content was much lower. Dispersion of the flexural mode, which causes a spreading of the signal in time over increasing propagation distance, is the dominant mechanism for this high attenuation. As shown in the transverse matrix cracking study, simple analysis of relative plate mode amplitudes is useful for source discrimination in coupons where the source to sensor propagation distance is small. However, these results suggest that careful consideration of attenuation effects will be required to extend this approach to larger specimens such as panels or realistic structures.

As requested by the workshop organizers, additional comments on the generalization of these results are included in the concluding remarks. In particular, it is noted that although Modal AE analysis has been successfully used to discriminate source mechanisms in composite materials, further research is required before the approach can be used in arbitrary materials, laminates, and/or specimen geometries. Further developments in modeling AE wave propagation which may provide insight into the effects of different source mechanisms on AE waveforms, will likely speed this process. It is also suggested that automated waveform analysis approaches such as pattern recognition and neural networks will be most successful at source discrimination when based on knowledge of wave propagation. Furthermore, factors such as attenuation and complicated structural geometries must be carefully considered when extending Modal AE analysis to the testing of large specimens and real composite structures.

2. Modal AE

A number of early AE studies, including those by Pollock (1986), Stephens and Pollock (1971), Egle and Tatro (1967), and Egle and Brown (1975), made passing mention of the propagation of AE waves as guided acoustic modes in practical testing geometries such as coupons, plates, shells, pipes, and rods. However, these works offered little as to the importance of these modes on the interpretation and analysis of AE with respect to source location accuracy and identification of source mechanisms. In fact, Pollock (1990) raised these same questions in a review paper on critical problems for research in AE. At about this same time, Gorman (1991) and Gorman and Prosser (1991) published work on the effects of guided wave AE propagation in plates. It was pointed out that in thin plates and coupons, the two observed modes of propagation in AE signals are the extensional and flexural plate modes. The predominant particle displacement for the extensional mode is in the plane of the plate. The largest component of the flexural mode particle displacement is out of the plane of the plate. A source motion with predominantly in-plane components and symmetric about the midplane generates AE signals with large extensional mode components. Examples of such a source motion include fatigue cracking in metals and matrix cracking in the center plies of a composite laminate. Out of plane source motion such as delamination or impact damage produces AE signals with large flexural mode components. This discovery led to a waveform analysis method to identify sources and discriminate noise signals and is the basis for the Modal AE technique.

The extensional mode propagates with a faster velocity and suffers little dispersion over the frequency range observed in most AE experiments (20 kHz to 1 MHz). It typically contains higher frequency components than the flexural mode. The flexural mode, however, propagates with a slower velocity and is highly dispersive with the higher frequencies traveling at higher velocities. A typical waveform detected in a composite plate with a broad band sensor identifying these two modes is shown in Fig. 1. The source of this signal was a simulated AE event caused by a pencil lead fracture (Hsu-Neilsen source) on the surface of the composite plate.

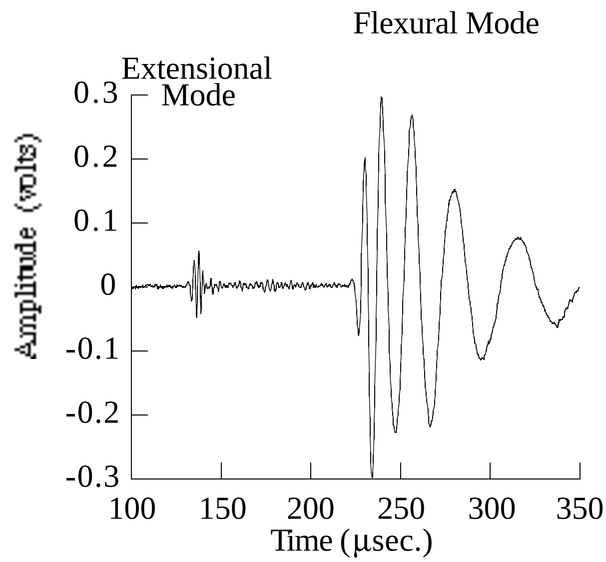


Fig. 1 Simulated AE signal in composite plate identifying extensional and flexural plate modes.

3. Detection of Transverse Matrix Crack Initiation in Cross-Ply Laminates

The initiation and progression of transverse matrix cracking in composite materials has been, and remains, a subject of considerable interest and importance. A vast amount of literature on the experimental detection of matrix cracks is available, of which, a small sampling is reviewed by Prosser et al. (1995). The improved source location accuracy and enhanced noise discrimination capabilities of the Modal AE technique are demonstrated in this study of the transverse matrix crack initiation in cross-ply laminates of different stacking sequences. This work improved upon a recent similar study by Gorman and Ziola (1991) in which and only a single cross-ply laminate was tested.

Tensile coupon specimens (2.54 cm. wide by 27.94 cm. long) of AS4/3502 graphite/epoxy composite material were loaded in tension under stroke control (0.127 mm/minute). As grip noise was eliminated by waveform analysis, specimen end tabs were not used in these tests. Specimens from six different cross-ply laminates were tested. The stacking sequences were [0_n, 90_n, 0_n] where n ranged from one to six. Thus, the samples varied in thickness from 3 to 18 plies.

Broadband, high fidelity sensors (Digital Wave Corporation B1000) were used to detect the waveforms. Rather than a single sensor at either end of the specimen as in many previous works, four sensors were used. At either end of the nominally 152 mm. specimen gage length, a pair of sensors were positioned. The outer edge of each 6.35 mm diameter sensor was aligned with the edge of the specimen. A diagram of a specimen showing the sensor positions and the grip regions is shown in Fig. 2. The motivation for this sensor array arrangement was the determination of the initiation site of the crack. Not only could the linear location along the length of the specimen be determined, but lateral location information was also obtained. The maximum digitization sampling frequency (25 MHz) of the digital AE acquisition and analysis system (Digital Wave F4000) was used to provide the most accurate location results. Location was performed, post-test, using manual, cursor based phase point matching on the extensional mode for arrival time determination. The extensional mode velocities used for the location analysis were measured prior to testing using simulated AE sources.

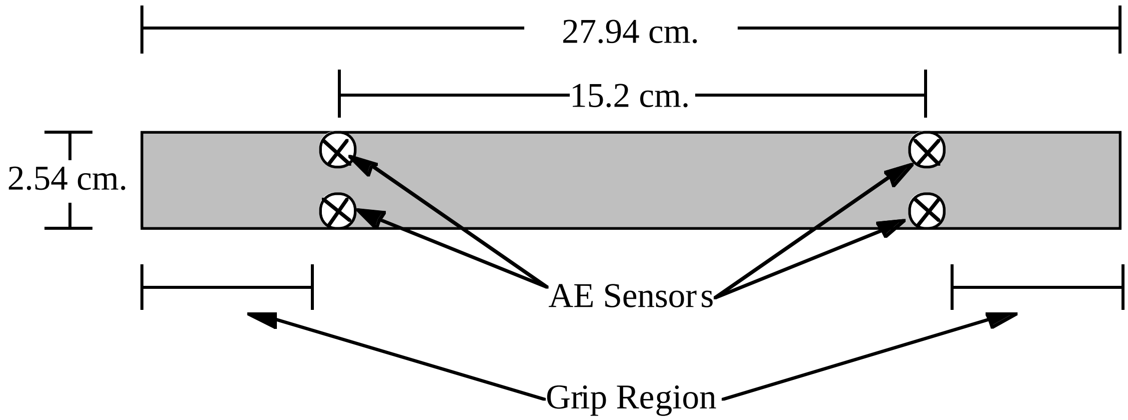


Fig. 2 Diagram of specimen showing grip region and position of AE sensors

After detection, the signals were amplified 20 dB by wide band preamps (Digital Wave PA2040G). It was determined during the tests that the signal amplitudes were a function of the 90 degree layer thickness, so additional system gain was varied to maintain the signal within the dynamic range of the 8 bit vertical resolution of the digitizer. Thicker specimens generated signals of larger amplitude. The additional system gain ranged from as little as 6 dB for the thickest specimen to 18 dB for the nine ply specimen (n = 3). For the three and six ply laminates (n = 1 and 2), the signal amplitudes were significantly smaller as will be discussed below. For these, the preamp gain was increased to 40 dB and the system gain was set as high as 18 dB in attempts to capture the much smaller amplitude signals.

After detection of one or more transverse matrix crack AE signals, the specimen was removed from the test machine. One edge of the specimen, which had been polished prior to testing, was examined under an optical microscope. The specimen was mounted on an x-y translation stage to allow measurement of crack locations for comparison with the AE data. Backscatter ultrasonic scans were taken to further confirm the crack locations and to provide information about the lateral extent of the cracks. This method also confirmed that no cracks existed which were not detected at the one polished edge. In some cases, penetrant enhanced radiography was also used as was destructive sectioning and microscopy.

Extraneous noise signals were eliminated by post test analysis of the waveforms. Typical waveforms from both a crack source and a noise source are shown in Fig. 3. Because of the multiple reflections of the signals across the narrow width of the coupons, the signals are more complicated than those presented in Fig. 1 which were detected in a large plate. However, the high frequency extensional mode is clear in the crack signal. A small extensional mode component is observed in the noise signal followed by a much larger, low frequency, dispersive flexural mode signal. The source of the noise signals is believed to be grip damage or specimen slippage in the grips as all of the noise signals located outside the specimen gage length in the grip regions.

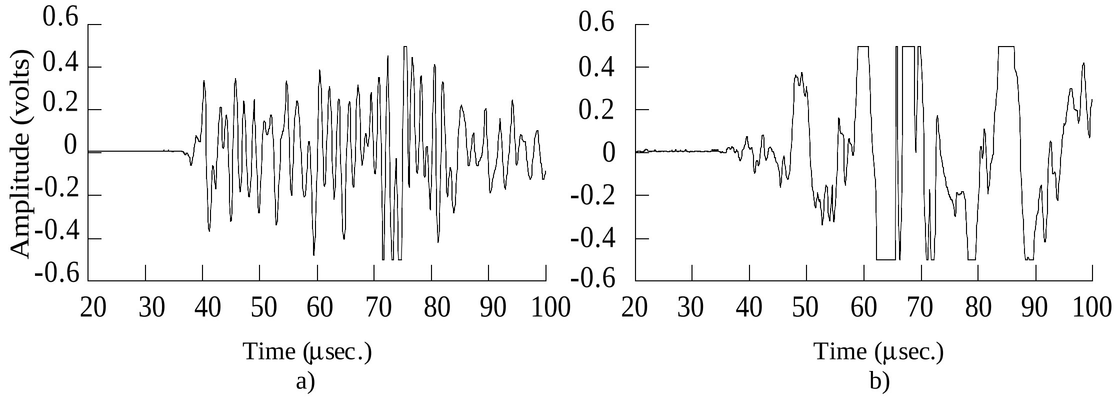
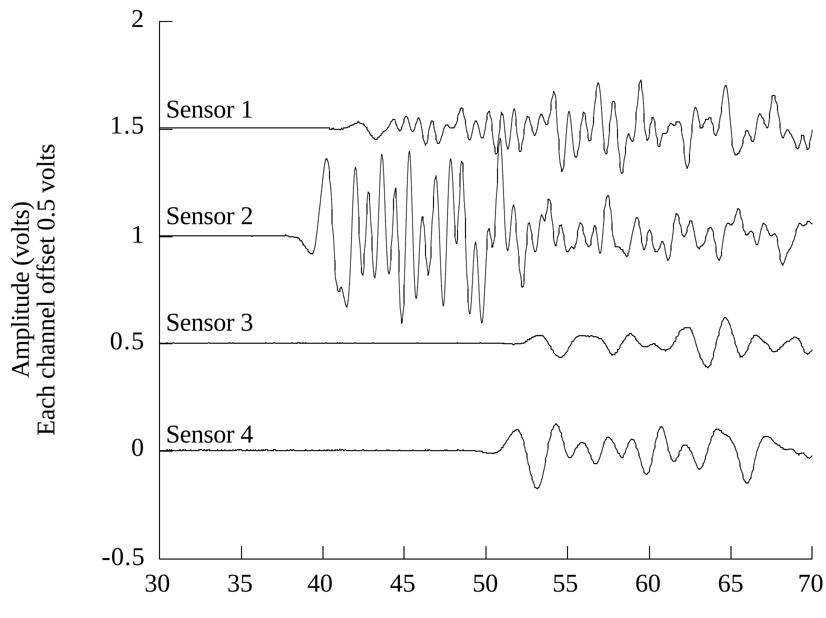


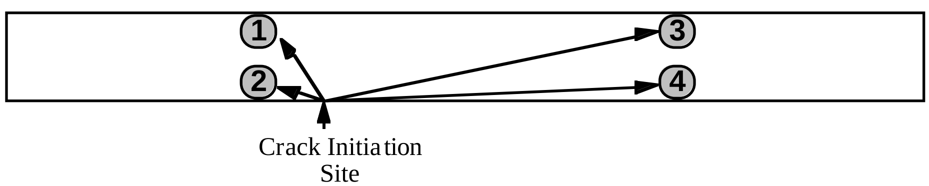
Fig. 3 Typical signals caused by a) transverse matrix crack and b) grip slippage or damage

For the laminates with n = 3 or larger, there was an exact one-to-one correlation between AE crack signals and cracks confirmed with microscopy. Backscatter ultrasonics indicated that all of these cracks extended across the full width of the specimen and that none were present which were not observed by microscopy of the polished edge. Destructive sectioning and microscopy of a few of these cracks also confirmed this result. The fact that only a single AE signal was detected for each crack indicates that the cracks immediately propagated across the width of the specimen.

Location analysis of the four sensor array data showed that all cracks initiated along one of the specimen edges. A typical four channel set of waveforms from a matrix crack signal is shown in Fig. 4 along with a diagram indicating the sensor positions and the crack location. The time delay between the sensor pairs associated with the crack initiation site being located along the edge is clearly seen. Furthermore, differences in signal amplitudes between the sensors within a pair are the result of the increased attenuation from propagation across the specimen width. The differences in signal amplitudes and frequency content for signals detected at opposite ends of the specimen and thus different distances of propagation distances should also be noted. These differences, which are caused by attenuation and dispersion, can have significant effects on location accuracy in threshold based arrival time AE measurement systems. Conventional amplitude distribution analysis is also affected by this attenuation. Excellent crack location accuracy along the length of the specimens was also obtained from the AE data as compared to microscopy measurements. The most accurate linear location was obtained by using the two sensors on the same edge as the crack initiation site. The average of the absolute value of the difference in crack locations from AE and microscopy was 3.2 mm for a nominal sensor gage length of 152 mm.



a)



b)

Fig. 4 a) Set of four channel waveforms indicating crack initiation along the specimen edge and b) diagram showing sensor positions, crack initiation site, and rays of direct propagation for the AE signal.

For the thin laminates (n = 1 or 2), the AE signals from cracks were not always successfully detected and the signals detected were significantly smaller in amplitude. Ultrasonic backscatter scans and destructive sectioning microscopy analysis showed that the cracks, which were visible at the specimen edge, did not extend into the interior of the specimen. Thus, the cracks were again initiating along the edge, but not progressing immediately across the specimen. This difference in crack initiation and growth behavior explains the much smaller amplitude signals and the difficulty in detecting these cracks.

4. Plate Mode Attenuation

As illustrated by the measurements above, Modal AE analysis provides the capability to differentiate AE signals from damage from those caused by extraneous noise in laboratory testing of composite coupons. Other studies such as by Ono and Huang (1994) have suggested that Modal AE waveform analysis can identify and differentiate signals from other source mechanisms such as delamination and fiber breakage. However, to apply these concepts to the testing of large structures, careful consideration must be given to the attenuation behavior of the different guided modes over longer distances of propagation. This includes signal loss in both the virgin material and that due to structural elements such as joints, stiffeners, or coatings. As an example, Prosser (1996) presented measurements of the effects of cryogenic insulation on the attenuation of plate modes in composite laminates. In this research, measurements of far field, peak amplitude attenuation were made for the extensional and flexural plate modes propagating in two different thicknesses of a virgin, uncoated, composite plate.

Attenuation is the loss of amplitude of an acoustic wave with propagation distance. As discussed by Pollock (1986), there are four contributing factors to attenuation. These are 1) geometric spreading of the wave, 2) internal friction, 3) dissipation of the wave into adjacent media, and 4) losses related to velocity dispersion. As discussed and demonstrated by Pollock (1990) and Downs and Hamstad (1995), geometric spreading is the dominant source of attenuation in the near field close to the source. For two dimensional wave propagation in geometries such as plates, the amplitude decreases inversely as the square root of the distance of propagation. This can lead to significant attenuation greater than 40 dB over the first few centimeters of propagation. For plate waves, the attenuation over this region will be even greater as the signal begins to separate into the distinct modes and suffer from velocity dispersion.

In the far field, attenuation is typically dominated by absorption or conversion of sound energy into heat. Absorption usually has an exponential relationship of attenuation with distance. An attenuation coefficient, A, with units of dB/unit distance can be measured. For plate waves, the transition distance at which exponential attenuation begins to dominate geometric spreading is given by 4.34/A.

Another mechanism of attenuation is amplitude loss due to dissipation into adjacent media. This can be caused by inhomogeneities in the medium which scatter the sound wave within the same material. Examples are grain structure within metals and fiber reinforcement in composites. It can also be caused by a medium in contact with the material or structure under test. A classic example relevant to AE testing is where acoustic waves propagate out of a pipe or pressure vessel into the contained fluid. Another instance is that of amplitude losses due to structural elements such as ribs and stiffeners. Amplitude losses of this type can be considerable and must be carefully evaluated when applying AE to practical structures.

The final attenuation mechanism is that of signal loss due to velocity dispersion. Because of the different velocities for different frequency components, an initially short, broad band, pulse, begins to spread in time at increased distances of propagation. This causes a loss in amplitude. The magnitude of amplitude loss depends on the steepness of the dispersion curves and the bandwidth of the signal. Previously, in most AE research and testing, narrow band resonant acoustic sensors have been used. Likewise, most ultrasonic measurements are made with narrow band tone burst input signals, and bulk wave propagation with little or no dispersion is studied. Thus, dispersion induced attenuation is seldom observed and has been little studied. However, as demonstrated by the following measurements, this mechanism of signal loss is of considerable importance for analysis of broad band Modal AE signals. Flexural mode attenuation, as measured by far field peak amplitude signal loss with propagation distance, was significantly larger than that of the extensional mode. This was true even though the extensional mode peak contained much higher frequencies which are typically more severely attenuated by absorption and scattering mechanisms.

Measurements were made of the loss in peak amplitude as a function of propagation distance in the far field for both the extensional and flexural plate modes in two graphite/epoxy plates. Measurements were made along the 0, 45, and 90 degree propagation directions. The two plates were different thicknesses of quasi-isotropic laminates of IM7/977-2 graphite/epoxy. Both plates had nominal lateral dimensions of 0.99 X 0.99 m. The first plate was 0.12 cm. thick (8 plies) and the second was 0.37 cm. (24 plies). Both plates were C-scanned with conventional ultrasonics prior to testing and determined to be of good quality.

For these measurements, a simulated AE source (pencil lead break) was used. For each propagation direction, the source was positioned 0.127 m from the plate edge. A sensor (Physical Acoustics Corporation R15) was placed next to the lead break source to provide a trigger source for the digital waveform recording system (Digital Wave Corporation F4012). This system digitized the signals with 12 bit vertical resolution and recorded 4096 points at a sampling frequency of 5 MHz. The preamplifier and system gain was individually adjusted for each channel to provide a measurable, unsaturated signal. A linear array of five, broad band, high fidelity AE sensors (DWC B1025) along the propagation direction was used to detect the simulated AE signals. The sensor nearest the source was at a distance of 10.16 cm. with the other sensors spaced at equal distances of 10.16 cm. apart along the propagation direction.

The peak amplitudes of both the extensional and flexural mode components of the signals were measured at all sensor positions. The measured amplitude values (in dB) were corrected for differences in preamp and system gain and plotted as a function of propagation distance. A linear least squares fit was then used to determine the attenuation. As expected in a quasi-isotropic laminate, the attenuation was nominally the same for the three measured propagation directions (0, 45 and 90 degrees). Typical plots of peak amplitude versus distance for both the 8 and 24 ply plates are shown in Fig. 5.

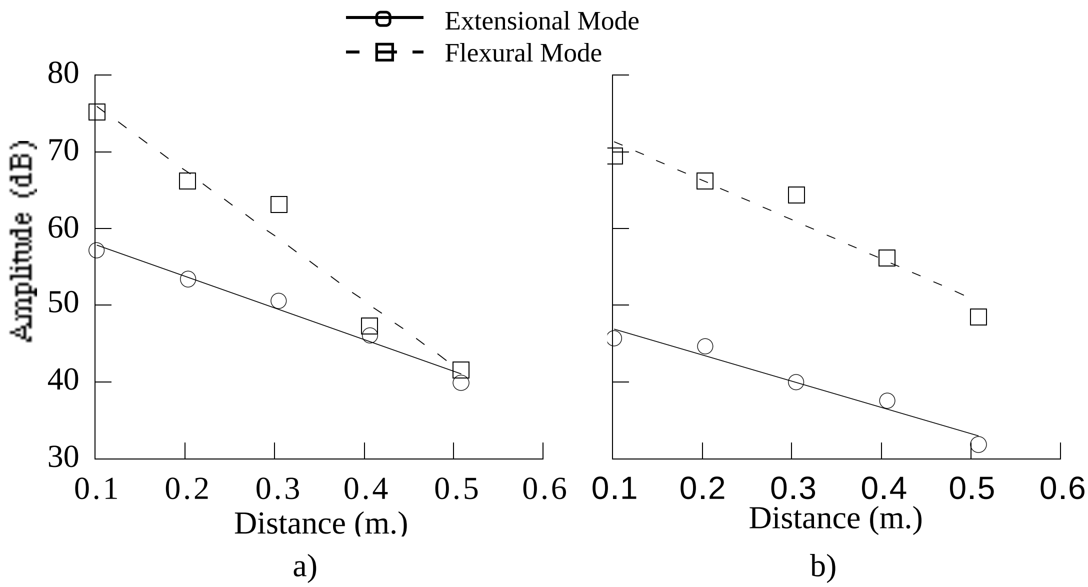


Fig. 5 Peak amplitude versus propagation distance for extensional and flexural modes in a) 8 ply composite plate and b) 24 ply composite plate.

The average attenuation of the extensional mode for the three propagation directions in the 8 ply plate was 42 dB/m. Variations in attenuation from the average along the different directions were no greater than +/- 3 dB/m for all measurements to be discussed. For the flexural mode, the average attenuation was significantly larger at 83 dB/m. This large difference in attenuation between the two modes should have a great impact on sensor placement decisions on larger structures dependent on the mode of signal desired to be detected. Furthermore, if comparisons of the relative amplitudes of the modes are to be made to differentiate source mechanisms and noise, corrections for this different attenuation will be required. This large difference in attenuation between the extensional and flexural modes was measured even though the frequency content of the flexural mode near the peak was much lower than that of the extensional mode. An estimate of the peak frequency was made from the measurement of the half period of the cycle on which the peak amplitude was measured. The frequency of the extensional mode peak was 410 kHz while it was only 85 kHz for the flexural mode peak. Absorption and scattering losses, which are usually the dominant far field attenuation mechanisms, significantly increase with frequency in composite materials. Thus, based on the frequency content, one would expect the extensional mode attenuation to be larger. However, examination of the actual waveforms confirmed the large affect that dispersion has on reducing the amplitude of the flexural mode.

For the thicker, 24 ply plate, the average attenuation of the extensional mode was 35 dB/m. This is slightly less than that in the thin plate. This might be expected since the measured peak frequency was also less at 230 kHz. At 51 dB/m, the flexural mode attenuation was considerably less than in the 8 ply plate, although still larger than that of the extensional mode. The estimated peak frequency was 90 kHz which was comparable to that in the thin plate. In this thicker plate, the waveforms at different distances showed much less spreading in time due to dispersion than in the thinner plate. This observation is consistent with the smaller measured attenuation value.

5. Observations and Conclusions

As suggested by the meeting organizers, the following discussion offers not only direct conclusions from the presented measurements, but also comments as to their generalization to the larger field of composite materials research. The two sets of data presented, at the same time demonstrate the potential benefit of Modal AE, as well as some its current limitations. The successful detection of transverse matrix cracking in cross-ply graphite/epoxy composites with thick 90 degree layers shows the capability to identify a particular source mechanism and differentiate noise signals. Excellent source location results were obtained. Not only was the position of the cracks along the specimen length determined and in excellent agreement with microscopy results, but the lateral position of the crack initiation site was also determined. In these coupons, all cracks initiated along one of the specimen edges.

The difficulty in detecting matrix cracking in similar specimens with thin 90 degree layers illustrates a couple of points. First, the same source mechanism can produce AE signals with significantly different amplitudes. In this case, the amplitude was dependent on the thickness of 90 degree plies and the length of crack advance. A similar result might also be expected for other source mechanisms such as delamination. In a real structure, it is anticipated that the length of advance for a given crack or delamination might vary considerably dependent on local stress conditions. Furthermore, damage will occur in different layers which might have different thicknesses. These factors cast considerable doubts on the capabilities of conventional amplitude distribution analyses for differentiating source mechanisms. This is especially true in light of the considerable effects of attenuation which are demonstrated in the second set of measurements.

The second point involves the generalization of the Modal AE technique. Other studies, for example Ono and Huang (1994), have demonstrated success in identifying signals from different source mechanisms such as delamination or fiber breakage. However, considerable research advances are required before the technique is able to differentiate a number of source mechanisms in arbitrary materials, laminates, and or specimen geometries. Currently, AE signals in each new type of specimen must be carefully characterized and studied. Furthermore, at least for initial specimens, other techniques such as microscopy should be used to confirm the ability to use AE to identify a particular source mechanism in a particular material/laminate/geometry. Developments in modeling AE wave propagation will aid in expanding the applicability of Modal AE by providing insight into the effects of different source mechanisms on observed AE signals.

Another important point is that the results obtained in this study were obtained from manual, one-at-a-time waveform processing. This further restricts the generalization of the approach. Techniques such as pattern recognition and neural networks have significant potential for automating Modal AE analysis. However, it is stressed that they should be based on a sound understanding of wave propagation in order to be most successful in identifying source mechanisms. Wave propagation effects can make initially similar AE signals from the same source mechanisms appear very different and vice versa.

The attenuation measurements demonstrate the marked difference in amplitude loss for the extensional and flexural plate modes. Dispersion is the dominant mechanism for flexural plate mode attenuation. Thus, it is affected by plate thickness and material properties. To extend Modal AE analysis beyond testing small laboratory coupons to larger specimens and practical structures, attenuation effects will need to be well characterized and corrections made for amplitude measurements.

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